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PERFORATION OF A REINFORCED CONCRETE WALL BY A RIGID MISSILE

by

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PERFORATION OF A REINFORCED CONCRETE WALL BY A RIGID MISSILE

[PERFORATION D'UNE PAROI EN BETON ARME PAR UN PROJECTILE RIGIDE]

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AUTHOR'S SUMMARY

The results are given here of a large experimental programme. Cylindrical steel projectiles were fired at slabs of reinforced concrete. A scale of one-third with respect to the wall of a nuclear reactor was largely used, and the effects of the variation of the following parameters were studied: projectile speed, mass, ratio of diameter of projectile to thickness of slab, and the characteristics of the steel reinforcement.

A homogeneous perforation formula is proposed for the computation of the thickness of reinforced concrete which will be perforated by a given missile, and its range of validity is specified. A comparison with other formulae found in the literature is made. Page 2

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1 INTRODUCTION

Analysis of the safety of nuclear power stations has led to studies of the consequences of an aircraft crashing upon the containment vessel of a reactor. The nature of this catastrophic event being complex, it was necessary, in order to be able to make approximate calculations, to consider two simple models:

(i) The crushing of a deformable missile, for example the fuselage, on the vessel. The interest in this case is in the overall integrity of the wall without analysing in detail the stresses in the area of impact.

(ii) The impact of a rigid missile, for example engines, on a concrete wall. The interest in this case is in the local effect, and the object is to determine whether the missile perforates the wall or not.

Keywords, HARDENED STRUCTURES, PENETRATION, SURVIVABILITY, GREAT BRITAIN.

The two problems were addressed by CEA/DEMT. The first was relatively easy to deal with. This was because the calculated stresses could be taken up by the pre-stressed cables, or remain within the elastic limit for the types of steel employed.

The second problem is, on the other hand, more involved; to define it better, it must be recognised that, on the one hand, the missiles may have masses approaching several tonnes, with speeds of 20-200 m/s, and on the other hand, concrete walls may vary from 20 cm to 2 m. To simplify matters, the case of cylindrical missiles was first considered. Their diameter may be greater than 1 m. In point of fact, the important parameter is the ratio of the thickness of the concrete wall 'e' to the diameter 'd', and its range of interest to us is from 0.4 to 4.

Expressions experimentally derived for military missiles are well known. The principal ones have been brought together in the first part of the table, after adaptation to make them usable in the international system of units. (For comparison, the expression known as 'CEA-EDF' derived during this study, has been added at the bottom of the table.) The symbols used are as follows:

- M mass of the missile (kg)
- S its surface area (m^2)
- d its diameter (m)
- N a form factor for the nose of the missile
- V speed of impact (m/s)
- σ concrete compressive strength (Pa)

H thickness of the concrete wall in the case when it is not completely perforated (m)

e maximum thickness of a concrete wall which may be perforated by a given missile (m)

X depth of penetration in a wall of thickness H (m)

X_∞ depth of penetration in a wall of infinite thickness (m)

e_n 2.718.

There are two series of expressions: those giving the depth of penetration of a missile in concrete generally supposed to be of infinite thickness, and those giving the minimum thickness of the concrete wall which will be perforated by the missile.

It is noted that the areas of validity of these expressions are perhaps unknown, or perhaps outside the area which interests us, because they were established for velocities which are too great, and for ratios of e/d which are too large. Additionally, the application of these different expressions to a given situation provide us with very different results as we shall see further on, by an example.

For this reason some trials were decided upon to find a means of calculation, and to validate it as much as possible within the area of variation of the parameters defined above.

2 METHODS EMPLOYED FOR TRIALS

Several sets of trials were carried out at the Aquitaine Centre for Scientific and Technical Studies (CESTA) of the Atomic Energy Board, using a 300mm diameter compressed air gun, on slabs 1.46 by 1.46 m. Different techniques, for example, a wooden sabo at the rear of the missile, allowed the diameter of the latter to range from 100-300 mm, the mass from 15-300 kg, and the missile to have any shape. In each one of these trials, the object was to obtain a speed of impact equal to, or slightly above that which was just necessary to perforate the slab.

3 RESULTS OBTAINED UP TO THE PRESENT TIME

The whole trials programme is not yet completed, but already some important results have been obtained. The principal characteristics of the firings have been presented elsewhere[1,2].

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3.1 The process of perforation

In the case of a firing which causes perforation, the sequence of events examined on film is as follows:

(a) On impact, a shock wave crosses the slab at the speed of sound and is reflected by the opposite wall, usually causing spalling of the rear face: over a certain diameter, all the concrete situated between this face and the nearest layer of steel reinforcement is reduced to small pieces and is ejected at high speed.

By measurement of the speed of ejection V_e , and making a rough estimate of the mass ejected from the measured mean diameter spalled off and the depth of concrete dislodged, it was possible to deduce that the energy dissipated by this spalling is around 25% of the kinetic energy of the missile before impact.

(b) The missile then penetrates the concrete while rapidly losing speed, fracturing it in a more or less conical volume and breaking the first layers of steel reinforcement.

(c) The missile continues without a large change in speed, while pushing before it a quantity of broken concrete.

(d) Finally the missile is retarded by the rearmost layers of steel reinforcement which break under the stress.

(e) The missile continues beyond the other side of the slab with a speed termed the residual speed.

In the case of a firing which does not cause perforation, there are the following phases:

- shock wave and spalling of the rear face if the energy is sufficient;
- rapid decrease in missile speed on impact;
- a much slower reduction until zero speed and the rebounding of the missile.

In Fig 1 are shown the curves for the penetration of a flat-nosed missile of 34 kg and 278 mm diameter into a slab of 208 mm thickness comprising four equidistant layers of twisted steel reinforcing of 8 mm diameter and having a pitch of 12 per metre. The four curves correspond to four firings carried out with impact speeds lower or higher than the critical speed, on practically identical slabs. (There are some slight differences in the resistance of concrete to compression.)

3.2 Trials to determine an overall expression

We define as the critical speed the minimum speed of impact at which the missile perforates the slab.

The trials carried out did not permit any significant difference to be discerned in the results obtained with slabs whose density of reinforcing steel varied from 100-250 kg/m. These same results do not seem affected by the fact that the four layers of steel reinforcement employed in each case may be either equally spaced throughout the thickness or situated two by two in the neighbourhood of the faces. However, the absence of steel reinforcement on the rear face reduces the critical speed. This reduction is of the order of 10% when there is reinforcement only in the neighbourhood of the front face.

3.2.1 Estimation of the critical speed

We sought an expression giving a relationship between the critical speed and the characteristics of the slab and the missile. The number of trials in which perforation was just achieved is clearly insufficient to obtain this relationship. It is necessary also to make use of the results of other trials in calculating for each case the corresponding critical speed.

Knowing the speed of impact V and the residual speed V_r of the missile after perforation of the concrete slab, the critical velocity is calculated by the expression

$$V_c = V^2 - \frac{\left(1 + M_b\right)}{M} V_r^2$$

in which M_b is the estimated mass of the quantity of concrete pushed forward by the missile, and assumed to have the same speed.

3.2.2 Search for an expression

We looked for a dimensionless expression. Examination of the dimensionless parameters $\rho V^2/\sigma$, $M/\rho d^2 e$ and e/d led to the empirical relationship:

$$V_c^2 = 1.7\sigma\rho^{\frac{1}{3}}\left(\frac{de^2}{M}\right)^{\frac{4}{3}} .$$

In Fig 2 is shown the relationship of the expression to all the firings which caused perforation under the following conditions: reinforcing steel greater than or equal to 100 kg/m^3, placed either symmetrically or uniquely on

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the rear surface, and concrete with a resistance to compression of between 28 and 45 MPa.

The results of firings causing perforation, carried out on a larger scale by EDF, have also been shown in Fig 2. From these is deduced the expression known as 'CEA-EDF', which allows the calculation of the thickness necessary just to achieve perforation with a given missile:

$$e = 0.82\sigma^{-\frac{3}{8}}\rho^{-\frac{1}{8}}\left(\frac{M}{d}\right)^{\frac{1}{2}}V^{\frac{3}{4}} \quad .$$

Evidently these expressions must be applied using a consistent system of units.

On the other hand, it would be prudent at present to consider the expression applicable only in the range which has been validated by the trials, *ie*:

- reinforcing steel:	100-250 kg/m^3
- resistance to compression of the concrete:	28-45 MPa
- density of concrete:	2500 kg/m^3
- characteristic parameter $\frac{M}{de^2}$:	2000-100000
- cylindrical flat-nosed missile.	

In particular, for the values of M/de^2 less than 2000, corresponding approximately to speeds greater than 200 m/s, it appears that the expression provides values of critical speed distinctly less than those obtained experimentally for a number of firings.

3.3 Steel-reinforced slabs of less than 100 kg/m^3

A number of trials were carried out on slabs without steel reinforcement or having only weak reinforcement. The results obtained are compared with the expression in Fig 3.

4 EXAMPLE OF AN APPLICATION OF THE EXPRESSION: CRASH OF A MILITARY AIRCRAFT

Fig 4 gives the results of calculations carried out with both the earlier expressions and the new expression in the case of the engine of a military aircraft of 1.6T and of 1 m diameter, incident upon a wall of reinforced concrete having a breaking load under compression of 400 bar. The thickness of the concrete wall which may be perforated is shown as a function of the speed of impact.

It is to be noted that, having eliminated the ACE and NDRC expressions which are obviously inapplicable to low speeds (at zero speed, the thickness of perforated concrete would be respectively 1.90 and 1.30 m); there still remains a factor of an order of 10, between the thicknesses perforated, as given by the expressions of PETRY and BETH. The new 'CEA-EDF' expression is the only one whose validity can be assured in the case considered, and in this example the danger can be readily seen of the use of empirical expressions outside their range of validity.

5 STUDIES IN HAND

5.1 Ageing of concrete

The expression was established following trials on slabs aged for 28 days. It is known that the resistance of concrete to compression continues to increase while ageing and may attain, for example, 60 MPa after 10 years in certain cases.

We first tried special concretes having good resistance after 28 days. The results obtained are compared with the expression, in Fig 5. Such concretes are in fact less resistant to perforation than would be indicated by the expression.

A second series of tests is also in hand. For this, concretes employed for the construction of power stations are to be used, and will be submitted to firings at different ages. These studies will thus require time, and conclusive results are not yet available.

5.2 Influence of the shape of the missile

The expression has been established for a flat-nosed cylindrical missile. From trials in hand, it would appear still to be valid for the case of a non-circular flat nose on condition that an equivalent diameter calculated for the same section is employed. This is no longer the case if the nose is not flat; a missile corresponding to a quarter of an electric power station turbine constructed without blades, at a scale of 1/4.5, was able to perforate a slab of concrete only at a speed 50% greater than that calculated by the expression, taking an equivalent diameter corresponding to the same projected section.

5.3 Calculation of the degradation of concrete on impact

The PLEXUS code[3] is used. In its current version, it is a two-dimensional finite element code for large displacements and non-linear plastic deformations. It was envisaged specially for calculations on structures submitted to loads applied at high speed and capable of causing their destruction.

The concrete model put into this code includes three rules:

(a) Shearing rule: Fig 6 illustrates the theoretical curve (continuous line) and the plot of the model under consideration (dashed line). For each value of the confining pressure $\sigma_2 = \sigma_3$ there is a curve of the change of stress $\sigma_1 - \sigma_3$ as a function of deformation.

(b) Rule of variation of volume: Fig 7 illustrates the theoretical curve (continuous line) and the plot of the model (dashed line). These curves provide the variation in volume of the concrete as a function of the confining pressure P.

(c) Failure under tensile stress: when the stress reaches the limit of tensile fracture within a cell, the tensile forces are reset to zero.

A first attempt at calculation was made by estimating the numerical values for the concrete model, as a result of information found in the literature. The axisymmetrical mesh chosen for a non-reinforced slab is represented in Fig 8, where the missile, also in the form of a mesh, is at the top left. Fig 9 shows the penetration at time $t = 1.5$ ms. This calculation was carried out by taking the characteristics of a trial carried out on a non-reinforced slab with a missile arriving at a speed of 114 m/s. The calculation demonstrates complete perforation, with a residual speed of 40 m/s. The actual trial had given a residual speed of 42 m/s.

The foregoing result is very encouraging, but the numerical values were put into the model from estimated values, and without any measurement having been effectively made.

Studies are in hand to try to determine the properties of concrete in a more rational manner, from measurements.

6 CONCLUSION

It has been possible to obtain an expression which is, as from now, being used by EDF for the determination of the thickness of reinforced concrete necessary for the safety of nuclear reactors in the event of an aircraft crash.

As with any experimental expression, its area of validity is determined by trials carried out. Trials in hand to enlarge on this should soon provide some knowledge of the influence of the ageing of concrete, and of the shape of the nose in the case of a non-cylindrical circular missile.

Further trials are envisaged to examine the case of speeds greater than 200 m/s.

The results already obtained show that a method of calculation should soon be fully assessed, to deal with the degradation of concrete on impact and to allow valid results to be obtained in cases more complicated than a simple wall.

Table 1

VARIOUS EXPRESSIONS

	Penetration	Perforation	Area of validity	
PETRY (modified)	$X_\infty = K\frac{M}{S}\log\left(1 + \frac{V^2}{20000}\right)$	$e = 2X_\infty$	$H > 3X_\infty$	V ?
	$X = X_\infty\left[1 + e_n^{-4}\left(\frac{H}{X_\infty} - 2\right)\right]$		$2X_\infty < H < 3X_\infty$	$\frac{e}{d}$?
BRL	$X_\infty = 1.03\ 10^{-3}\ \frac{MV^{1.33}}{d^{1.8}\sqrt{\sigma}}$	$e = 1.3X_\infty$	V ?	$\frac{e}{d}$?
ACE	$X_\infty = 3.53\ 10^{-4}\ \frac{MV^{1.5}}{d^{1.785}\sqrt{\sigma}} + 0.5d$	$e = 1.32d + 1.24X_\infty$	$150 < V < 900$ m/s	$3 < \frac{e}{d} < 18$
NDRC	$G = 3.83\ 10^{-5}N\ \frac{MV^{1.8}}{d^{0.8}\sqrt{\sigma}}$	$e = 1.32d + 1.24X_\infty$	$150 < V < 900$ m/s	$3 < \frac{e}{d} < 18$
	$G \leqslant 1 \rightarrow G = \frac{X_\infty^2}{2d}$	ou		
	$G \leqslant 1 \rightarrow G = \frac{X_\infty}{d} - 1$	$e = 1.23d + 1.07X_\infty$		
BETH		$\frac{e}{d} = 3.19\ \frac{X_\infty}{d} \cdot\cdot\ 0.718\left(\frac{X_\infty}{d}\right)^2$	V ?	$3 < \frac{e}{d} < 18$
CEA-EDF		$e = 0.82\sigma^{-3/8}p^{-1/8}\sqrt{\frac{M}{d}}\ V^{3/4}$	$20 < V < 200$ m/s	$0.3 < \frac{e}{d} < 4$
			Flat nose 28.10^6 Pa $< \sigma < 45.10^6$ Pa	

REFERENCES

No.	Author	Title, etc
1	C. Berriaud A. Sokolovsky R. Gueraud J. Dulac R. Labrot	Local behaviour of concrete enclosures subject to the impact of a rigid missile. Nuclear Engineering and Design 45, 457-469 (1978)
2	C. Berriaud P. Verpeaux A. Hoffman P. Jamet R. Avet-Flancard	Test and calculation of the local behaviour of concrete structures under missile impact. Paper J7/1 - 5th SMIRT, Berlin, 13-17 August 1979
3	C. Chavant A. Hoffmann P. Verpeaux M. Dubois	PLEXUS - computer code for explicit Lagrangian computation. Paper B 4/8 - 5th SMIRT, Berlin, 13-17 August 1979

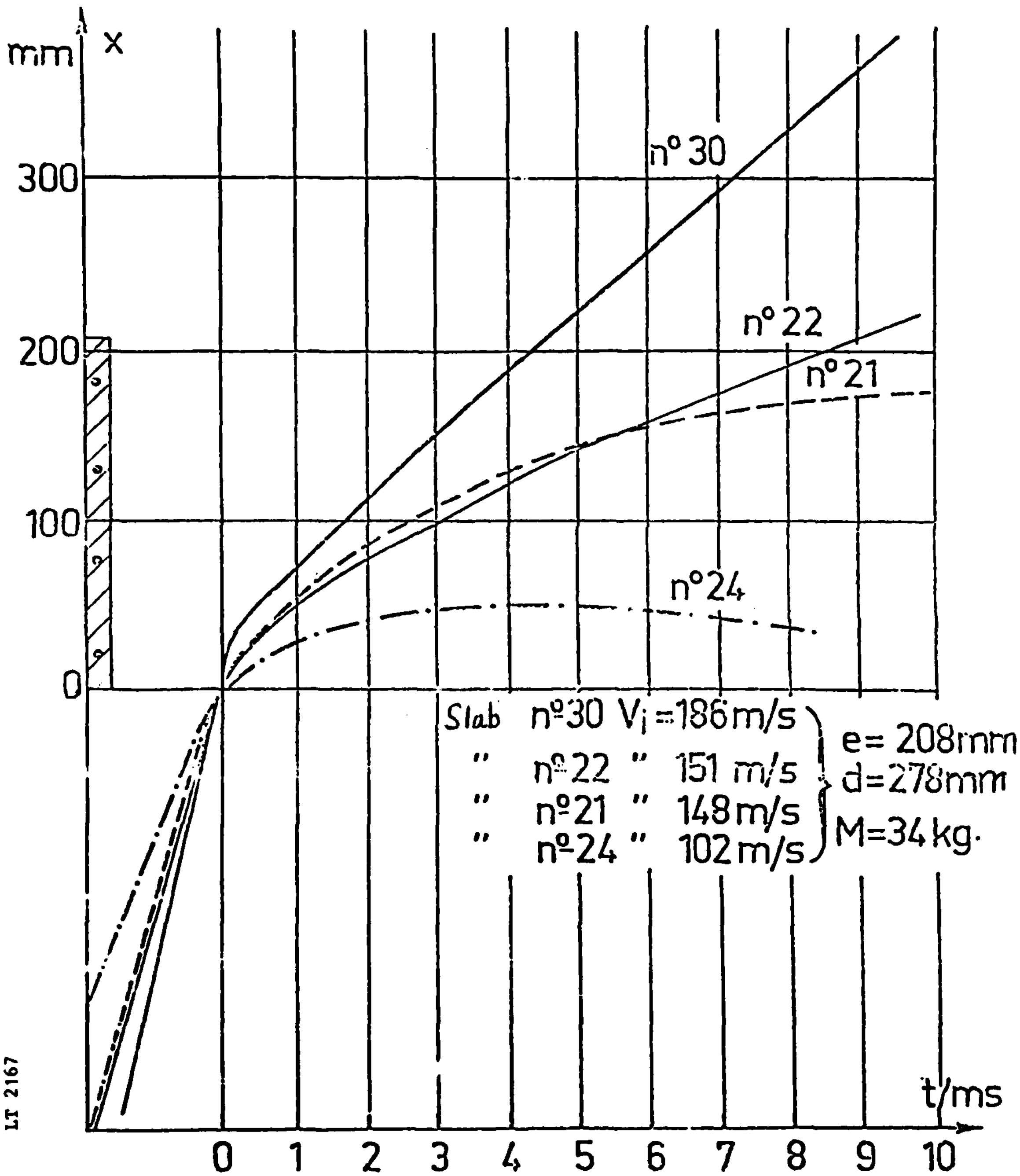
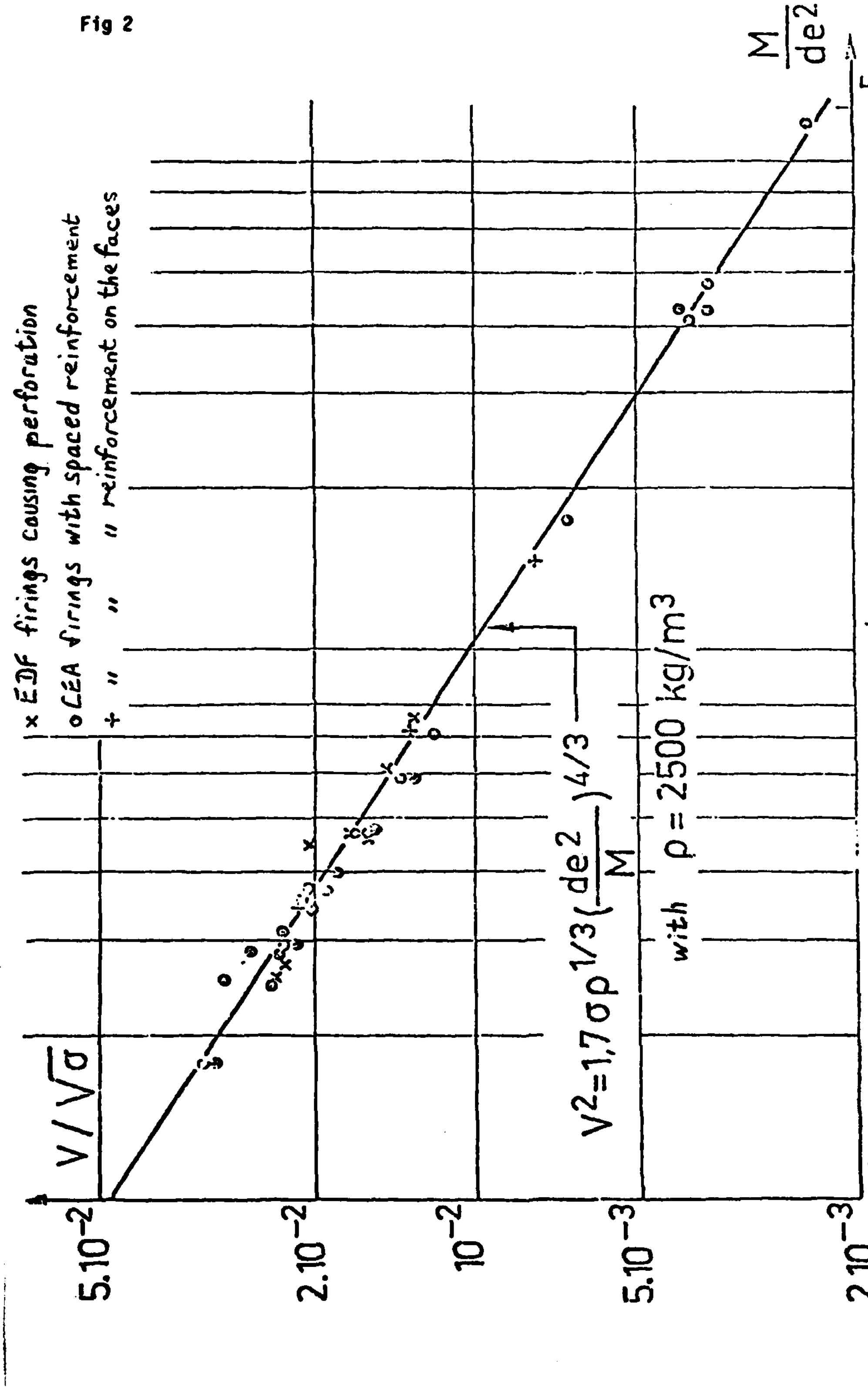

mm
x
300
200
100
0
n° 30
n° 22
n° 21
n°24
Slab n°30 V_i = 186 m/s
" n°22 " 151 m/s
" n°21 " 148 m/s
" n°24 " 102 m/s
e = 208 mm
d = 278 mm
M = 34 kg.
t/ms
0 1 2 3 4 5 6 7 8 9 10

Fig 1

Fig 2



V / √σ
5.10⁻²
2.10⁻²
10⁻²
5.10⁻³
2.10⁻³
10³
2
3
4
5
6
7
8
10⁴
2
3
4
5
6
7
8
10⁵
M / de²
× EDF firings causing perforation
o CEA firings with spaced reinforcement
+ " " " reinforcement on the faces
V²=1,7σρ^{1/3}(de²/M)^{4/3}
with ρ = 2500 kg/m³

Fig 2

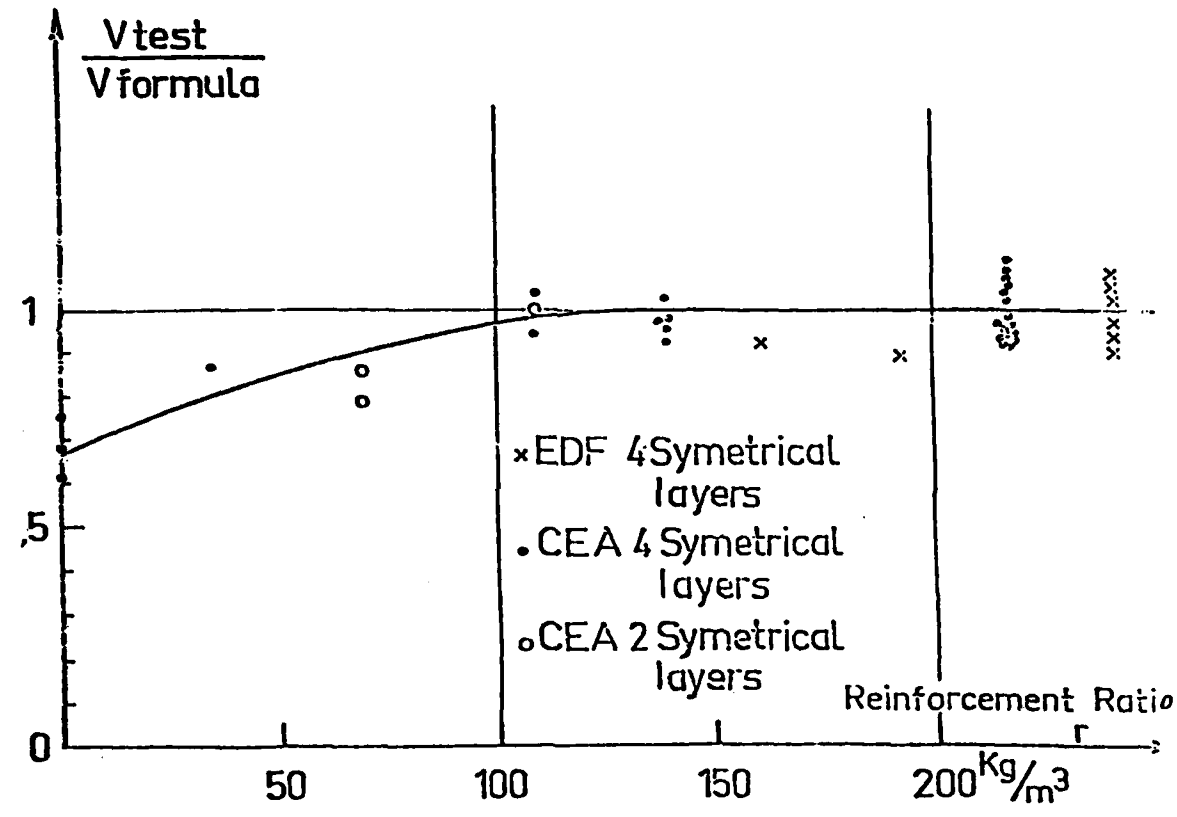

Vtest
Vformula
1
,5
0
50
100
150
200 Kg/m3
Reinforcement Ratio
r
× EDF 4 Symetrical layers
• CEA 4 Symetrical layers
○ CEA 2 Symetrical layers

Fig 3

Fig 3

Fig 4 THICKNESS OF CONCRETE PERFORATED

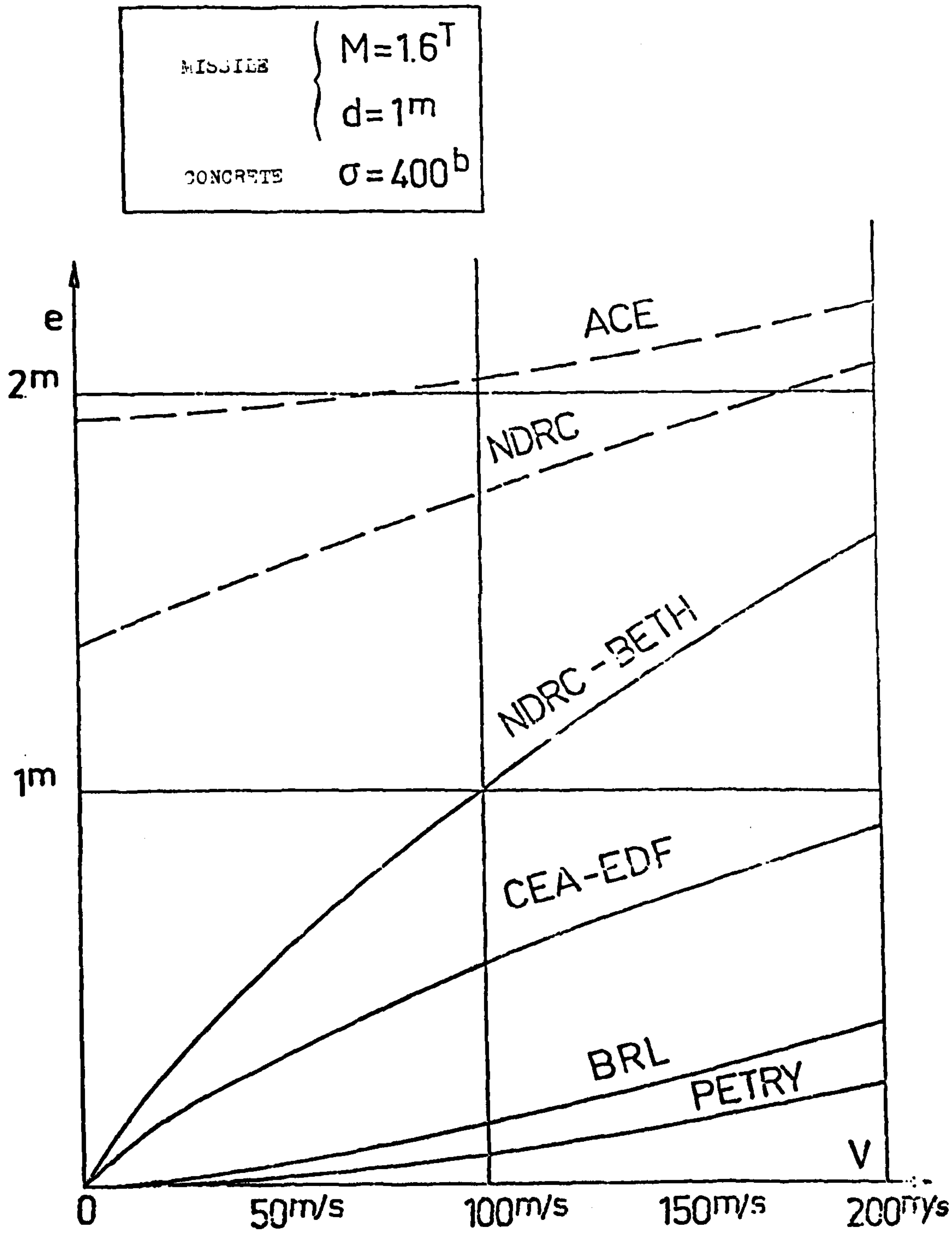


Fig 4

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Fig 5

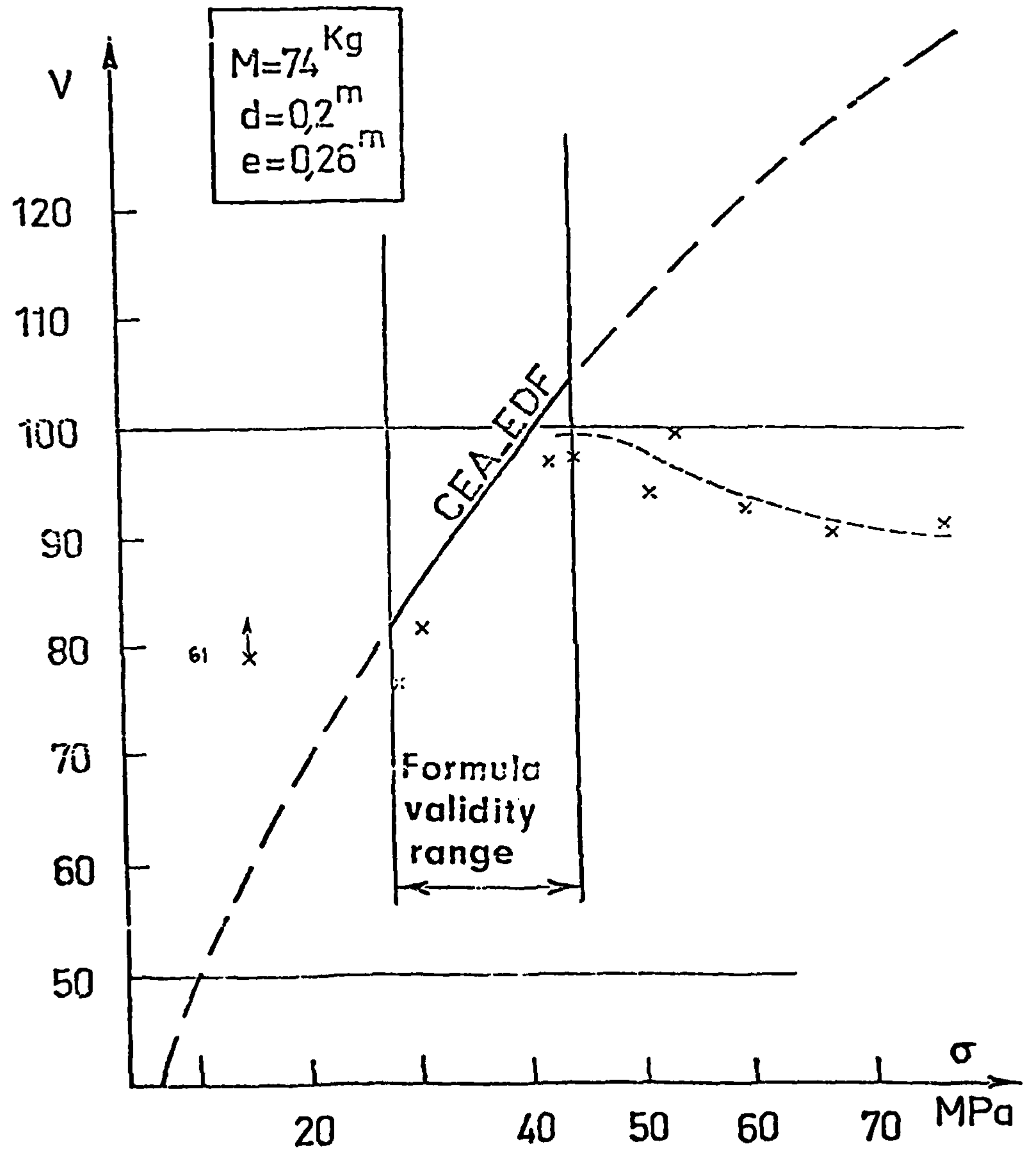

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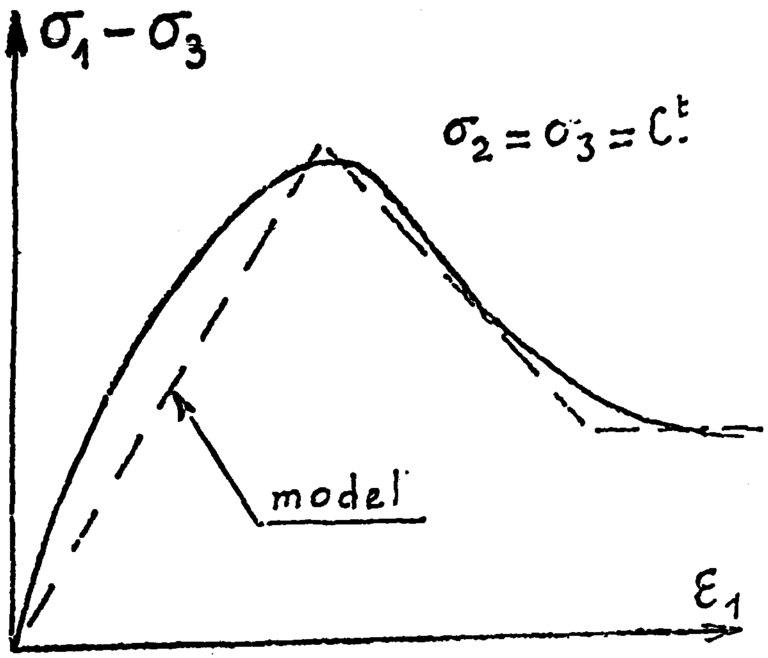
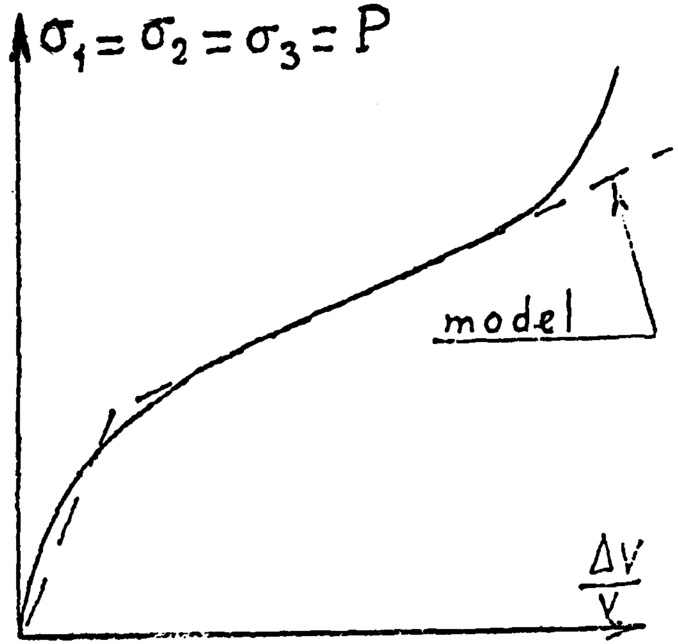
Fig 5



$\sigma_1 - \sigma_3$
$\sigma_2 = \sigma_3 = C^t$
model
ε_1

Fig 6



$\sigma_1 = \sigma_2 = \sigma_3 = P$
model
$\frac{\Delta V}{V}$

Fig 7

Figs 8&9

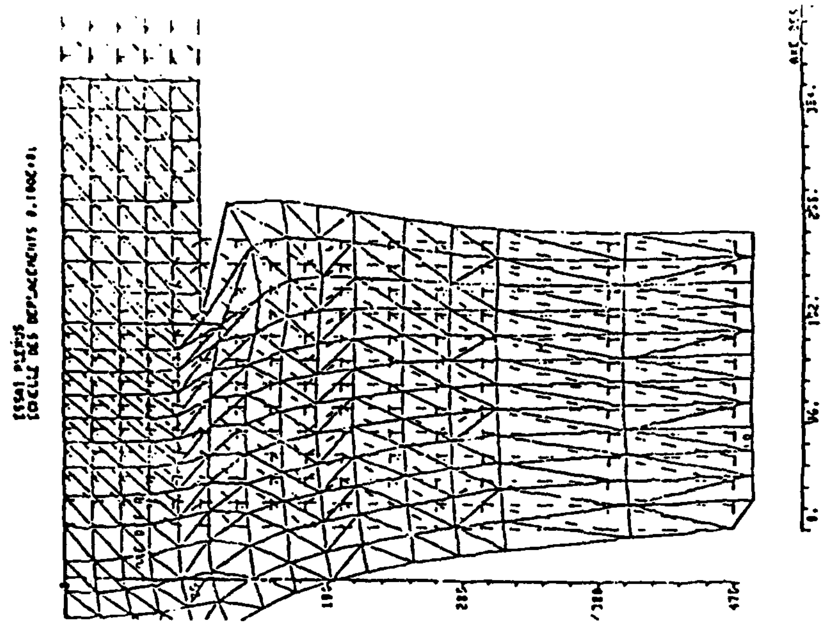


Fig 9

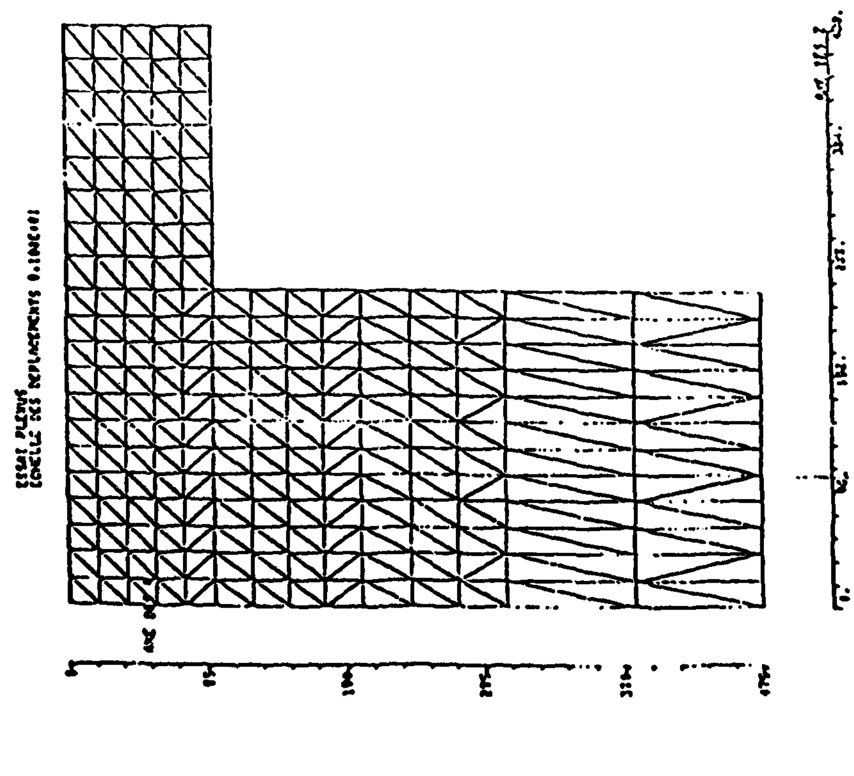


Fig 8